A Conceptual Framework for an Agile Asset Performance Management Process

Ahmed Noaman Karar, Ashraf Labib and Dylan Francis Jones, *University of Portsmouth, Portsmouth, UK*

Abstract

Purpose - Disturbances in terms of major crises such as pandemics, fluctuations in demand and oil price, energy consumption, and supply chain can significantly impair the maintenance programs effectiveness and efficiency. Hence, there is an urgent need for an agile asset performance management framework.

Design/methodology/approach – This paper's main objective is to design a comprehensive framework for an agile asset performance management system that sustains the desired asset performance by reacting efficiently, quickly, and intelligently to the changes in the operating context parameters and asset health conditions. Such a framework is adaptive to changes in scenarios and aims to systematise the decision support process, considering different objectives.

Findings - The development of the proposed framework has led to identifying an innovative way of seamless integration between crucial reliability and asset management tools. Also, the methodology implementation is expected to promote the practical use of its reliability tools and enable asset stakeholders to break silo working for clear communication around asset performance.

Originality/value – The implementation of the Agile Asset performance Management (AAPM) framework follows a new approach developed during this research and coined by the authors as the '8S approach.'

Keywords: Management, Availability, Reliability, Maintainability, Maintenance, Asset, Maintenance Modelling

Article Type: Research paper

1. Introduction

Over the past few years, the global business environment has gone through strong reformation waves due to the accelerated move toward industry 4.0 and the adoption of more automation and digitalisation. This made the world economy more dynamic, so the fluctuations in product demand and, consequently, production intensity became a vital part of the business. Also, availability, cost of spares, and raw material supply are additional variables here. Moreover, safety, environmental, and quality expectations of stockholders are frequently increasing. For instance, when oil prices increase, the need for more production rises, and the consequences of failures become more significant.

Furthermore, as the product demand rises, the stress on assets increases, and consequently, the probability of failure increases. On the other side, when oil prices go down, the focus shifts toward cost-cutting and spending less on maintenance, and also many assets switch from duty mode to idle mode. Oil price fluctuation is part of the business, and its consequences would be significant if not considered. The following chart (Figure 1) shows how NYMEX WTI crude oil's daily price had been fluctuating over six months (November 22, 2019, to May 22, 2020). The price shown is in U.S. dollars per barrel.

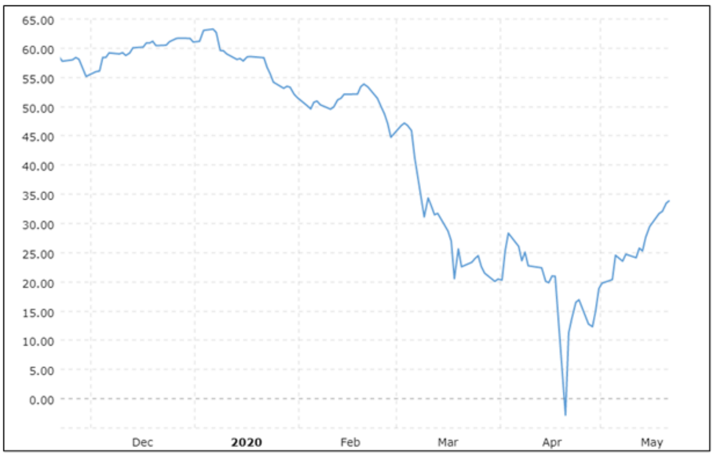

Figure 1: Crude oil price chart (macrotrends, 2020)

As a result of these continuous variations, the operating context changes from time to time; and as the operating context changes, some failure modes' likelihood and severity may vary, and perhaps the associated maintenance task needs to be modified. Of course, it is not practical for organisations to review and update all their maintenance programs every time the operating context changes, as this is time and effort consuming considering the massive number of assets they possibly have. For instance, the effort required to complete one maintenance program may vary between 10 to 20 working days, depending on the selected system size and implication. Assigning a team of 5 to 7 experienced staff as a cross-functional team full time for such a long period is costly. On the other hand, organisations cannot just deny that the operating context is changing, and the asset maintenance program recommended earlier was designed under a different operating context. Denying this fact implies risk ignorance that might not involve operational consequences only, but it probably extends to safety and environmental consequences.

Another example of the significant disruption that can affect production is significant disturbances due to external factors such as the current pandemic of Covid-19 (Coronavirus), which is having a major impact worldwide. It prompts us to reflect on the need to build new generations of risk, safety resilience frameworks, as suggested by Aven and Zio (2020). Therefore, the authors agree with Tomlin and Wang (2011) in that supply risks can be attributed to three categories, as discussed above: the disruption of supply caused by low likelihood events such as pandemics, natural disasters or terroristic activities, random yield due to capacity and quality issues, and price volatility resulting from fluctuating exchange rates or energy prices.

To survive in such a harsh dynamic environment, the organisations must react instantaneously with quick and swift actions, revealing the need for more agile work processes that enable risk reduction and smart cost-cutting. Hence, this paper proposes a conceptual framework for an agile asset performance management framework that can deal more effectively with the rapid changes of the operating context parameters.

2. Literature Review

Many traditional asset management processes have been used successfully for a long time. Still, these processes have to be reviewed and updated periodically to remain competent in accommodating today's quick changes in the business environment. When it comes to optimisation and smart cost-cutting, maintenance and asset management cost is most probably the first thing to be considered as it represents a significant percentage of the total operational cost in most industries. "Within many large-scale plant-based industries, maintenance costs can account as much as 40% of the operational budget" (Eti , et al., 2006, p. 1235). Also, Holgado, Macchi, and Evans (2020) have highlighted the impact of maintenance improvement and optimisation on production sustainability and achieving business objectives (Holgado, et al., 2020, p. 7304). That is why optimising maintenance and asset management cost is vital for a successful business as these costs are profoundly reshaping the final business profit. This literature review section is organised in such a way that it provides a rationale for constructing the proposed conceptual framework.

The *selection and prioritisation* process is the typical starting point in many improvement approaches to ensure a successful implementation. Adams, Srinivasan, A.k., and Gonzalez (2016) have addressed the need to better understand asset criticality changes as a pre-requisite for successful optimisation of risk and operational cost throughout the entire asset life (Adams, et al., 2016, p. 107). To accommodate the needs of today's business environment for a dynamic asset criticality assessment approach, Karar and Labib (2020) have proposed an agile asset criticality assessment approach using a decision-making grid as a starting point of the maintenance optimisation effort (Karar & Labib, 2020). Also, Dui, Si, Wu, and Yam (2017) proposed an importance measure for a system considering external factors (Dui, et al., 2017). Therefore, the *'Select Asset'* process is the starting point of the proposed conceptual framework.

Asset intensive industries require long-term and sustainable asset life management strategy to stay competitive. This strategy's planning involves collecting information, setting goals, translating goals to specific objectives, and setting up activities to achieve the objectives (Stenström, et al., 2016). Despite the benefits of asset life optimisation processes, it has a few fundamental hurdles to be overcome. One major problem is that it normally requires a preliminary reliability assessment based on a large amount of operation data (Lee, et al., 2013, p. 1). Wang, Yam, Zuo and Tse (2001) have proposed a comprehensive set of criticality related criteria for determining the level reliability requirements (Wang, et al., 2001). For these reasons, the framework authors consider the *'Set Expectations'* as a driving process.

Hajej and Rezg (2020) have highlighted the importance of tuning the maintenance strategy according to the production plan to consider the relationship between the production rate and the equipment degradation (Hajej & Rezg, 2020, p. 4469). Also, Labib, Williams, and O'Connor (1997) proposed an assessment based on an analytical hierarchy process (AHP) framework of *most likely scenarios* based on a combination of both economic and market conditions to specify the importance of stakeholders and prioritise the selection of appropriate maintenance strategy (Labib, et al., 1997). Besides, the proposed hybrid maintenance strategy approach by Sahnoun, Baudry, Mustafee, Louis, Smart, Godsiff, and Mazari (2015) has allowed the generation of more power at lower costs when implemented in an offshore wind farm. In their approach, the type of maintenance task to perform varies depending on the turbine operating context scenario. Where, if the chosen turbine has a low health state, then a conditional task is chosen. If the selected turbine wasn't maintained for over six months, then a systemic maintenance task is performed (Sahnoun, et al., 2015). Thus, the proposed conceptual framework includes the *'Specify Scenarios'* as a triggering process.

Selvik and Aven (2011) have presented an RRCM framework based on the existing traditional RCM, which improved the risk by incorporating additional features to the existing RCM methodology (Selvik & Aven, 2011). Also, Wu, Chen, Wu, and Wang (2016) proposed linking the components' importance to determining preventive maintenance priority (Wu, et al., 2016). In line with these research efforts, the proposed framework introduces the '*start analysis*' process as an enhanced revision of the traditional RCM.

Yang, Zhao, Peng, and Ma (2018) have addressed the impact of hybrid preventive maintenance on maintenance cost optimisation (Yang, et al., 2018). Zhou, Zhang, Li, and Weng (2015) also stated that most of the maintenance optimisation activities are usually static processes. In other words, after one analysis, the maintenance strategy will be fixed without considering further equipment conditions (Zhou, et al., 2015, p. 1). This challenge shows the need to maintain and manage more than one maintenance strategy in place dynamically and adaptively based on changes in scenarios. Each maintenance strategy, or combination of strategies, can be collectively called actions' package, so the authors include the *'shape packages'* process in the proposed framework.

When it comes to the execution of the optimised maintenance strategy, the current computerised maintenance systems (CMMSs), on their own, have been criticised in that they lack efficient and effective decision support (Labib, 1998, 2003, 2004), and (Carnero & Novés, 2006). Also, as concluded by Braaksma, Klingenberg, and Veldman (2013), the main issue in FMEA process is "solely rely upon expert judgement and that the expert knowledge required for this judgement is often not available because of isolation between design and process engineers" (Braaksma, et al., 2013, p. 1067). This may flag the need to integrate between the CMMS and the strategy optimisation database. Such integration is intended to adapt existing failure modes into the standard failure codes in the CMMS dynamically and adaptively to achieve a '*standardised execution'* of the failure coding process, which has been captured in the proposed framework.

As proposed by Stuchlý, Poprocký, and Kaczmarek (2016), the use of analytic methods enable evaluation of failure rate, mean time to failure (MTTF), mean time between failures (MTBF), reliability probability (Stuchlý, et al., 2016, p. 41), and availability. This evaluation of *results* is needed periodically to evaluate the effectiveness of asset management strategy based on CMMS data. The proposed framework coins this process as the 'supervise results'.

Piechnicki, Dos Santos, Loures, and Dos Santos (2020) have proposed the use of cost measures, process performance metrics, and risk assessment metrics to audit and track the results of the RCM implementation results (Piechnicki, et al., 2020, p. 8). Also, as highlighted by Gupta and Mishra (2016) in their SWOT analysis of reliability centred maintenance (RCM), the need for significant updates of RCM databases and the substantial input data required to support the method are among the main identified weaknesses in several RCM frameworks (Gupta & Mishra, 2016). The continuous improvement of the RCM database a vital step to maintain an evergreen framework; therefore, the 'Sharpen more' process is the last point in the proposed conceptual framework.

The following section will discuss the development of an agile asset performance management process, considering the previously mentioned observations and challenges.

3. Agile Asset Performance Management Processes

The implementation of the Agile Asset Performance Management (AAPM) framework follows a new approach developed during this research and coined by the authors of this work as the '8S approach' as depicted in Figure 2. The figure shows the eight fundamental processes of AAPM. In what follows in this section, the authors highlight each of the elements of the proposed framework.

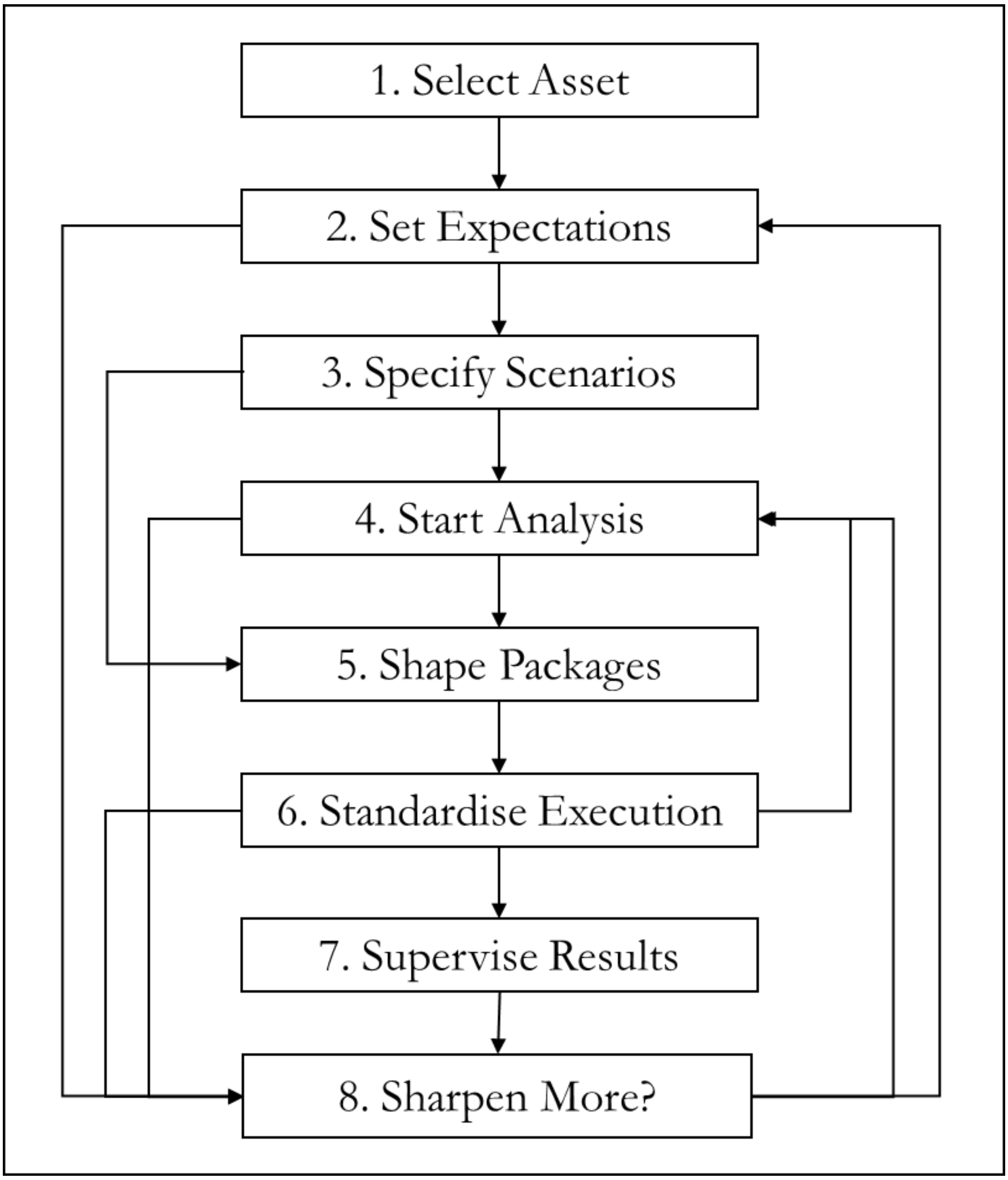

Figure 2: AAPM 8S implementation approach

3.1. Select Asset

Selecting which industries and at which level of asset hierarchy to start could be one of the leading factors determining the improvement program's success or failure. Working at a too low or too high hierarchy level would negatively impact the outcomes. Also, when there is no asset/system selection and prioritisation criteria in place, the management tends to propose the most expensive asset/system or the ones that cause the most production interruption cases (performance killer).

The most expensive and the performance killer are not necessarily the best selection for AAPM implementation. Moreover, they are sometimes the worst selection. The wrong choice of assets/systems for improvement will lead to lousy implementation results and failure to show the methodology robustness and ability to deliver results. Hence, assets/systems selection and prioritisation are essential within the AAPM framework to avoid program failure due to the assets' wrong selection.

Figure 3 presents the three fundamental pillars of assets/systems selection for AAPM: criticality, performance, and readiness. Also, the figure indicates priority numbers within the intersectional areas between the pillars, where 1 represents the highest priority, and 4 indicates the lowest priority. For instance, priority one is given to the high critical assets with poor performance and good readiness for AAPM. In contrast, priority four is allocated to the high critical assets with good readiness and performance.

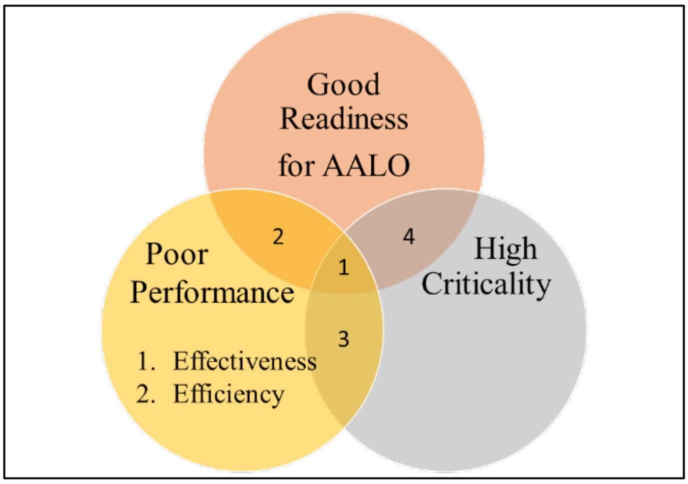

Figure 3: "Select asset" process

3.1.1. Readiness for AAPM

The readiness for AAPM represents the go/no-go gauge for the AAPM framework and considered to be an initial assessment phase. AAPM suggests a list of pre-requisite items needed before commencing the AAPM project. This checklist should answer the following questions:

- Are the right AAPM program expectations in place?
- Have the expectations been converted into measurable KPI's?
- Is there a project sponsor (leadership commitment)?
- Are the right people available to team up for AAPM, including an experienced facilitator?
- Is the level of engagement in place sufficient to complete the AAPM?
- Is it needed to hire an external subject matter expert (e.g. vendor, consultant, etc.)?
- Is the system preliminary reliability assessment completed (what is the current system performance)?
- Is the needed data available to proceed (e.g. drawing, OEM manuals, datasheet, computerised maintenance management system (CMMS) history, previous studies…etc.)?
- Is it ok to commence with the current data quality level?
- Is the risk assessment tool designed and ready for use?
- Is the final approver nominated with full responsibility to accept and implement the AAPM recommendations?
- Is there an agreement with the final approver on the AAPM audit, review and approve procedure?

The previous list of questions needs to be addressed before commencing the AAPM implementation, and If the answer to any of these questions is 'no', then it is better not to start the AAPM till it becomes 'yes'.

3.1.2. Performance:

Usually, the plant reliability analyst assesses the effectiveness and efficiency of the asset management strategy to make sure that the effective actions are planned well and executed efficiently. This is done through the periodic performance analysis to identify the systems causing the majority of losses in terms of the number of failures, repair cost, and production losses.

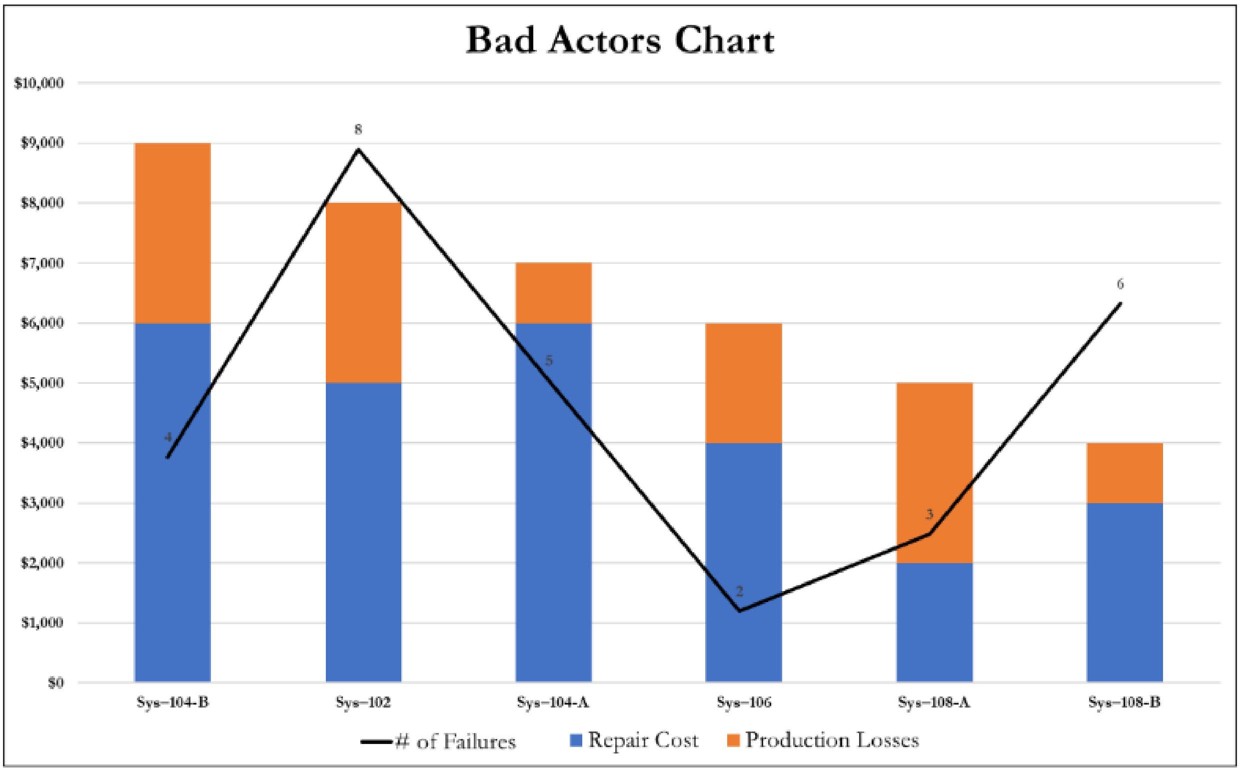

Figure 4: Bad actors' chart

Figure 4 depicts a Pareto chart for the performance of the six systems; it compares systems in terms of the number of failures, total cost, and production losses for a given period. Such a bad actor chart is reported periodically to the stakeholders to discuss and identify the causes of poor performance before initiating the proper mitigating actions accordingly.

3.1.3. Criticality

Asset criticality influences the priority of the CMMS daily work orders and gives higher priority to the ones linked to the high critical assets; also, it is one of the main selection criteria for improvement and optimisation projects. Therefore, the AAPM framework promotes the use of the agile asset criticality assessment process proposed by Karar and Labib (2020) as the two approaches were initiated in response to the accelerated fluctuation in today's business environment, which complement and enhance the suggested *"Select Asset"* process (Karar & Labib, 2020).

3.2. Set Expectation

Overselling the improvement initiatives takes all the blames for setting false expectations; this may happen as some asset management enthusiasts and practitioners' position asset performance management as a straightforward process. They do this to simplify the process and get the buy-in from stakeholders, which creates a false perception that there is no effort needed neither before the implementation nor after creating the recommendations. Additional blunder here is introducing asset performance management as the magic solution that can solve all asset management and reliability problems such as lack of training, poor communication with other departments, RAM data quality issues, and understaffing challenges. Also, not being honest in presenting challenges, effort, and time needed to implement is giving a false impression that asset performance management can deliver quick results.

Mirghani (2019) has introduced a performance-based approach to managing the implementation of a reliability-centred maintenance program. The methodology starts by reviewing the performance of the selected assets to justify the improvement opportunity in terms of cost, availability and reliability through benchmarking. This followed by a discussion with the plant's senior management to agree on the objectives and targets that covered reducing the outages and the cost per repair (Ahmed, 2020, p. 536).

Similarly, The AAPM framework proposes the "Set expectations" process starts with assessing the assets/systems status quo performance before discussing the expectations of asset's stakeholders in terms of reliability, availability, maintainability (RAM), cost, and risk. Thus, the correct implementation of this process reduces the probability of AAPM program failure due to wrong expectations. As depicted in Figure 5, the "set expectation" process output is the primary input to the "sharpen more" process, which uses this expectation as a reference to compare the asset/system performance against it.

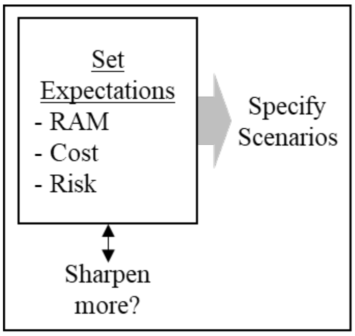

Figure 5: "Set expectations" process

3.2.1. RAM Evaluation:

The preliminary reliability assessment of asset/system performance is vital to complete before implementing the AAPM, as the assessment results form the baseline reference to assess the effectiveness of process recommendations later on. Suppose the initial assessment is cancelled due to data unavailability, and the organisation proceed to the implementation without preliminary reliability assessment. In that case, this will lead to an apparent failure in justifying the improvement results. Hence, the RAM evaluation task considers the results and trends of reliability, availability, and maintainability key performance indicators such as mean time between failures (MTBF), mean time to repair (MTTR), failure rate, and repair rate.

3.2.2. Cost Analysis:

This analysis covers the cost of preventive and corrective work, as follows:

1) Preventive work cost:

It consists of the cost of condition-based maintenance and pre-determined maintenance, which includes the cost of any production losses, spares, wages, and any additional cost consequences resulting from this maintenance activity.

2) Corrective work cost:

It considers the cost of immediate corrective maintenance and deferred corrective maintenance, which includes the cost of any production losses, spares, wages, and any additional cost consequences resulting from this failure.

3.2.3. Risk Assessment:

A preliminary risk assessment is included to understand the asset/system's risk profile before implementing the AAPM framework, which happens during a team brainstorming session to discuss the reasonably likely worst-case failure scenario and assess its probability and consequences. Also, this can be guided by the existing asset/system criticality ranking in place. Then, the team sets the expectations of the residual risk profile after the execution of AAPM, which defined in the form of acceptable risk thresholds.

3.2.4. Benchmark:

There are two types of benchmarking AAPM uses:

1) **Internal benchmarking:** It compares the asset/system performance against an identical asset/system with the best performance in the same plant.
2) **External benchmarking:** This performed through an agreement to exchange RAM data with similar companies working in the same industry, which allows the comparison of asset/system performance against identical ones but from other plants.

3.2.5. Discuss Expectations:

In light of the preliminary assessment results and the benchmarking records, the discussion with asset/system stakeholders sets specific, measurable, achievable, relevant, and timely (SMART) expectations.

3.2.6. Get agreement and commitment:

In the end, it is vital to document the agreed expectations and have them written so asset/system stakeholders read and understand them before they agree. The following table shows an example of stakeholders' agreement of expectations.

Table 1: Stakeholders' agreement of expectations template

No.	Performance Indicator	Performance		
		Results	**Benchmark**	**Expectations**
1	RAM Evaluation			
1.1	Reliability			
1.1.1	MTBF			
1.1.2	Failure Rate			
1.2	Availability			
1.2.1	Inherent Availability			
1.2.2	Achieved Availability			
1.2.3	Operational Availability			
1.3	Maintainability			
1.3.1	MTTR			
1.3.2	Repair Rate			
2	Cost Analysis			
2.1	Preventive work cost			
2.1.1	Condition-based work			
2.1.2	Pre-determined work			
2.2	Corrective Work Cost			
2.2.1	Immediate Corrective Work			
2.2.2	Deferred Corrective Work			
3	Risk Assessment			
3.1	Residual risk (acceptable risk thresholds)			

3.3. Specify Scenarios:

In some industries, the states and functions of assets change from time to time and season to season, which may involve the periodic shift in asset operating mode between duty and standby. These scenarios represent a big dilemma for any asset improvement approach starts from defining asset function, as setting the system function as a duty only means the implementation team has ignored the hidden failures that could happen during the standby mode time. On the other hand, describing the system as standby only involves the ignorance of wear and tear caused by duty time; hence, both assumptions will never lead to an optimum failure management policy.

Determine the operating context and the important components were the first part of the framework proposed by Martinetti, Schakel and Dongen (2018) to develop a scalable maintenance program for unmanned aircraft systems. They highlighted the importance of considering the operating context parameters changes and the need to provide "rules on how to encode operating contexts to manage these differences" (Martinetti, et al., 2018, p. 158).

Similarly, the AAPM "specify scenarios" process dissects the operating context parameters to precisely forecast the potential operating context scenarios. As depicted in Figure 6, the "specify scenarios" process categorises the operating context parameters into dynamic and static parameters to determine potential scenarios based on the different combinations of the operating context parameters' levels. Then, this process influences the "start analysis" process to create a dedicated actions' package for each scenario.

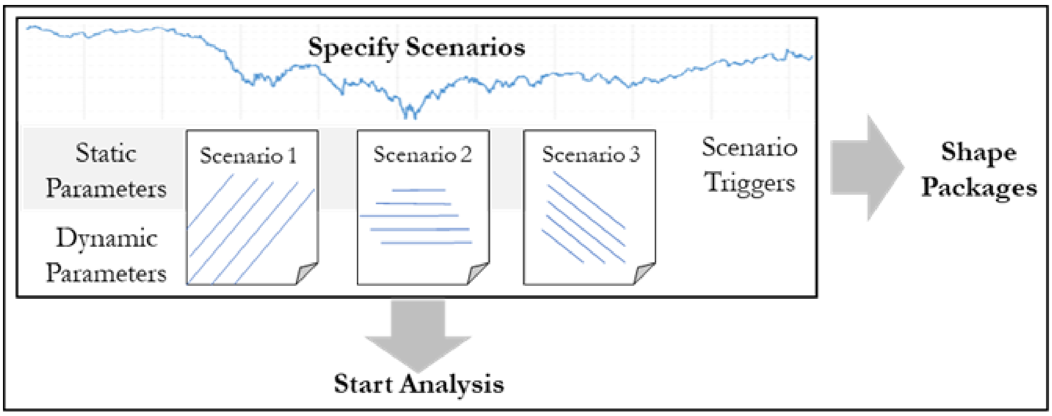

Figure 6: "Specify scenarios" process

3.3.1. Operating Context Parameters

Operating context parameters are the business environment variables that can influence and change what the stakeholders want from the asset/system. Examples of operating context parameters include market demand, raw material supply, spares availability, environmental conditions, working hours, quality standards, environmental standards, risk profile, plant design and configuration. These parameters are continuously changing; however, the rate of change is different from business to business; based on this rate of change, the AAPM framework classifies the operating context parameters into dynamic and static parameters.

1) Static Operating Context Parameters

This category covers a set of rarely changing parameters, such as HSE regulations, quality standards, asset/system configuration, and environmental conditions.

2) Dynamic Operating Context Parameters

This group includes all operating context parameters that change more frequently and directly impact the risk aspects. Usually, the cost and operation related parameters such as market demand, raw materials availability, and wages tend to be dynamic parameters. Figure 7 depicts a simple example of a production facility with only two operating context parameters; market demand and cost of energy. The figure shows a high market demand during spring and summer, while there is low market demand during winter and autumn, so the market demand has two levels high and low demand. Similarly, the cost of energy has two levels that are expensive and cheap.

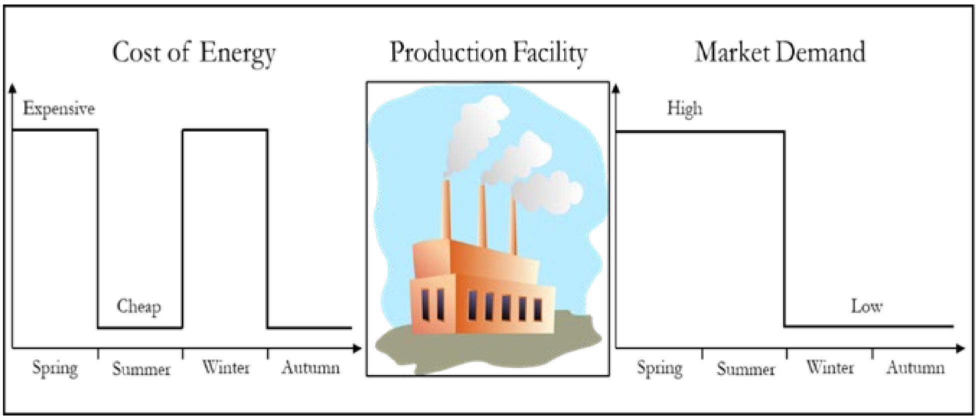

Figure 7: Operating context parameters and scenarios

3.3.2. Operating Context Scenarios List

The different combinations of parameters and states result in a list of potential operating context scenarios. As depicted in Figure 7, there are four operating context scenarios as follows:

- Operating context scenario 1: Expensive energy – high demand
- Operating context scenario 2: Cheap energy – high demand
- Operating context scenario 3: Expensive energy – low demand
- Operating context scenario 4: Cheap energy – low demand

3.3.3. The Dominant Scenarios

The dominant operating context scenarios have the highest probability, longer duration, and the most consequences. Thus, the *"start analysis"* process considers only the dominant scenarios during its eight steps, where the considered scenarios heavily influence the inherent and residual risk assessment steps.

3.3.4. Scenario Triggers

Scenario triggers are the changes in the operating context parameters that alert the asset owner of the transition from one operating context scenario to another. Considering the example given in Figure 7, once the market demand level changes from high to low and the cost of energy changes from expensive to cheap, these changes trigger the transition from scenario 1 to scenario 4. The following table shows an example of scenarios' triggers documentation.

Table 2: Operating context scenarios' triggers

Scenario #	Triggers	
	Cost of Energy	Market Demand
1	Expensive	High
2	Cheap	High
3	Expensive	Low
4	Cheap	Low

3.4. Start Analysis:

A standard part of most asset strategy improvement approaches is identifying the reasonably possible failure modes and assessing their consequences (SAE.JA.1012, 2002). There are different best practices in consequences assessment, but still, the process is subjective, which creates long debates during the implementation. These debates consume time and effort; also, they may lead in the end to wrong decisions and poor deliverables.

The "Start analysis" process proposes two dedicated steps to assess the inherent and residual risk in a more structured way. As depicted in Figure 8, the *"start analysis"* process considers the dominant operating context scenarios identified by the *"specify scenarios"* process through its eight steps. Also, it receives the work history updates from the *"standardise execution"* process to add a new failure mode or increase the probability of a listed failure mode. The output of the *"start analysis"* process is a list of AAPM actions transferred to the *"shape packages"* process to create an actions' package for each dominant operating context scenario. Finally, if the AAPM fails to meet the stakeholders' expectations, the *"sharpen more"* process will trigger the analysis review and update to find a better solution.

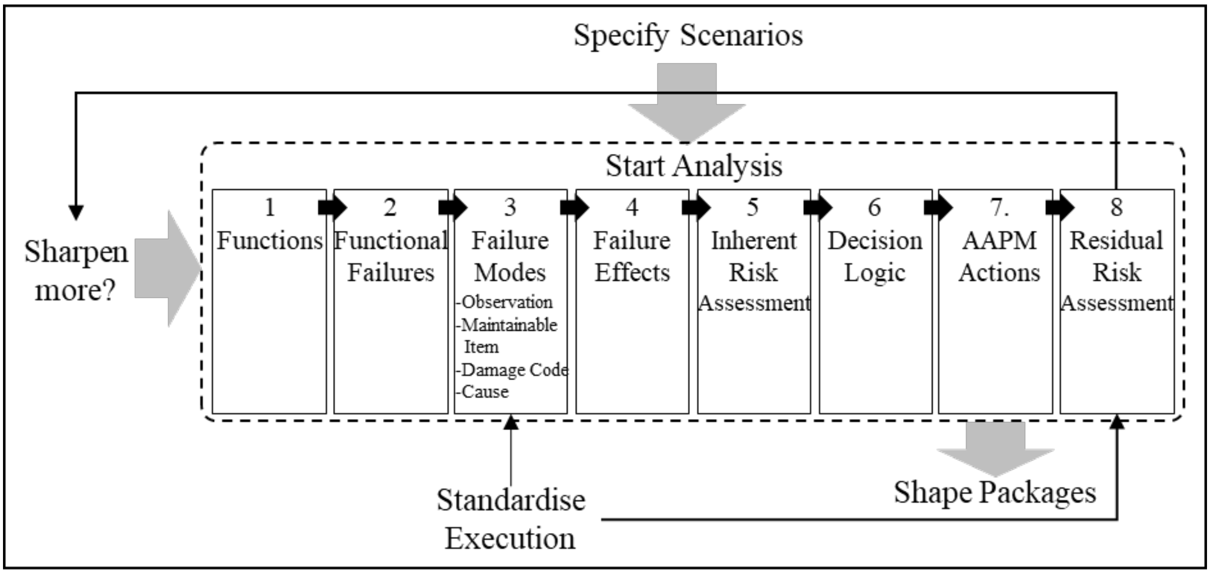

Figure 8: "Start analysis" process

3.4.1. Functions

Unlike the traditional reliability centred maintenance (RCM) process, the AAPM framework categorises system functions into two main types. This categorisation helps to optimise the effort needed to review and update the AAPM data with every operating context scenario change.

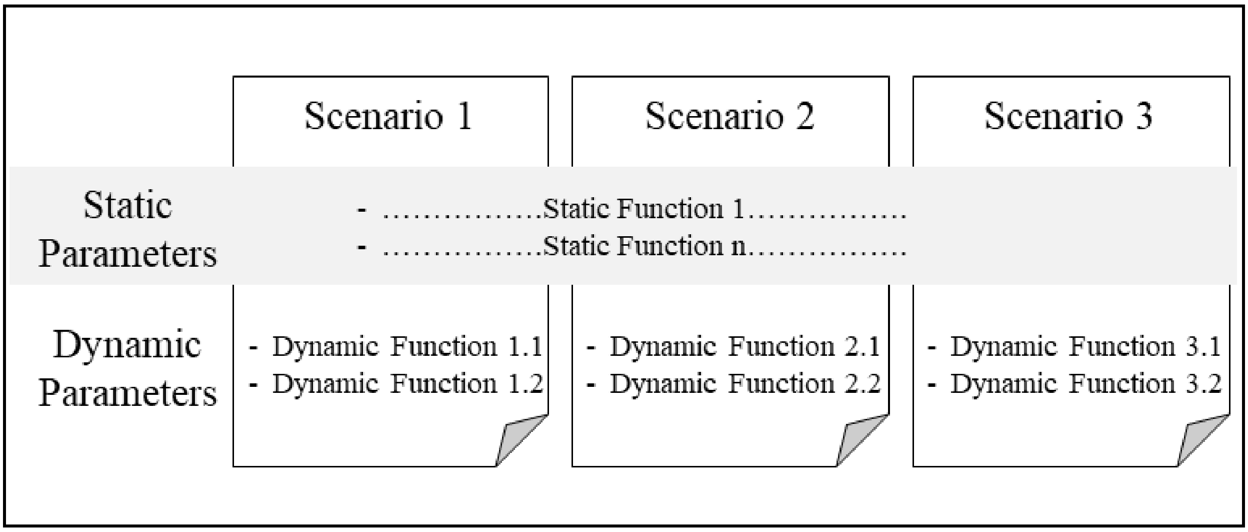

Figure 9: The types of AAPM functions

Figure 9 depicts the relationships between operating context scenarios, parameters, and the different AAPM functions types. These two types are static functions and dynamic functions categories.

1) Static Function

The static functions are those system functions that change only if the relevant static operating parameters change. These functions typically involve compliance with specific laws, regulations, and standards. For example, "to maintain the carbon monoxide (CO_2) emissions of a power generation unit below X" is an example of a static function where the standard performance value (X) is defined based on laws and regulations in place. Usually, the static functions are common across the dominant operating context scenarios, as shown in Figure 9.

2) Dynamic Function

The dynamic functions are the system functions that change as the operating context scenario changes. As depicted in Figure 9, each scenario has a different list of dynamic functions.

Considering the example given in Figure 7, in the dominant scenarios where the market demand is high, the function could be "to produce 1000±10 barrels/day of product X". While in the case of the dominant scenarios where the market demand is low, the function could be "to produce 500±5 barrels/day of product X". This reduction in productivity targets will reduce system profitability and result in more pressure for maintenance cost reduction.

3.4.2. Functional Failures

One functional failure has to be identified as per the traditional RCM process for each function, which depends on the quality of the function statement and the clarity of its performance standard. The following table gives an example of the functional failures' identification (SAE.JA.1012, 2002).

Table 3: Functional failures

Functions	Functional Failures
To produce 1000±10 barrels/day of product X	Unable to produce any barrels/day of product X
	To produce less than 990 barrels/day

3.4.3. Failure Modes

For each functional failure defined in the previous step, one or more failure mode has to be identified and discussed. The AAPM framework tries to bridge the gap between the standard RCM definition of the failure mode as per the SAE JA 1012 (A single event, which causes a functional failure) and the failure mode definition as per ISO14224 (the manner in which failure occurs). So, AAPM recommends four elements for every failure mode statement; these elements are observation, maintainable item, damage, and cause (ISO.14224, 2016).

For instance, "fail to start on-demand due to bearing seized due to lack of lubrication" is an example of an AAPM failure mode statement. Where "fail to start on-demand" is the observation, "bearing" is the maintainable item, "seized" is the damage, and "due to lack of lubrication" is the cause. As depicted in Figure 10, the inclusion of the observation, maintainable item, damage, and cause in the failure mode definition facilitates the integration with the *"standardise execution"* process. It allows the seamless updates of the AAPM database with any newly identified failure mode, which reduces the effort required to review and update the AAPM analysis.

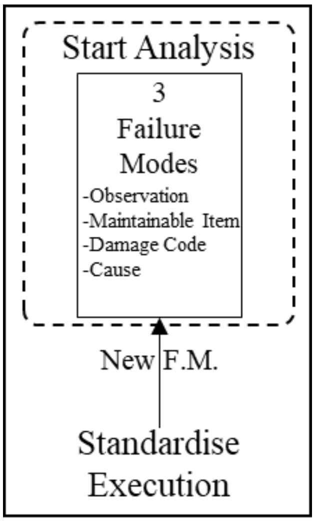

Figure 10: Failure modes' list update

3.4.4. Failure Effects

In AAPM, the failure effect statement explains the failure impact on safety, environment, operation, and any additional risk aspects. It also indicates how the failure been detected, the time to repair, and the resources needed to return the asset to service. Finally, this step documents the failure impact for every dominant operating context scenario to justify the risk assessment outcomes (SAE.JA.1012, 2002).

3.4.5. Inherent Risk Assessment

During this step, the AAPM team assesses the risk value of each failure mode assuming no maintenance (zero-based maintenance) and converts the failure effect statement into a quantitative risk. To accommodate the changes in the operating context scenario, the AAPM uses a three-dimensional risk assessment tool. An example of this tool was the risk assessment cube introduced by Lanzrath, Suhrke and Hirsch (2020) in their research to evaluate the risk of electromagnetic attacks on smart grid substations (Lanzrath, et al., 2020, p. 175).

Similarly, the proposed framework employees risk assessment cubes that cover each risk aspect, such as safety, environmental, operational and financial. As depicted in Figure 11, the cube evaluates risk using the two standard risk dimensions, which are likelihood and consequence, in addition to a third dimension that considers the applicable operating context scenarios. If the failure mode total inherent risk value exceeds the acceptable risk limit, then the following steps are required to assign a mitigating action.

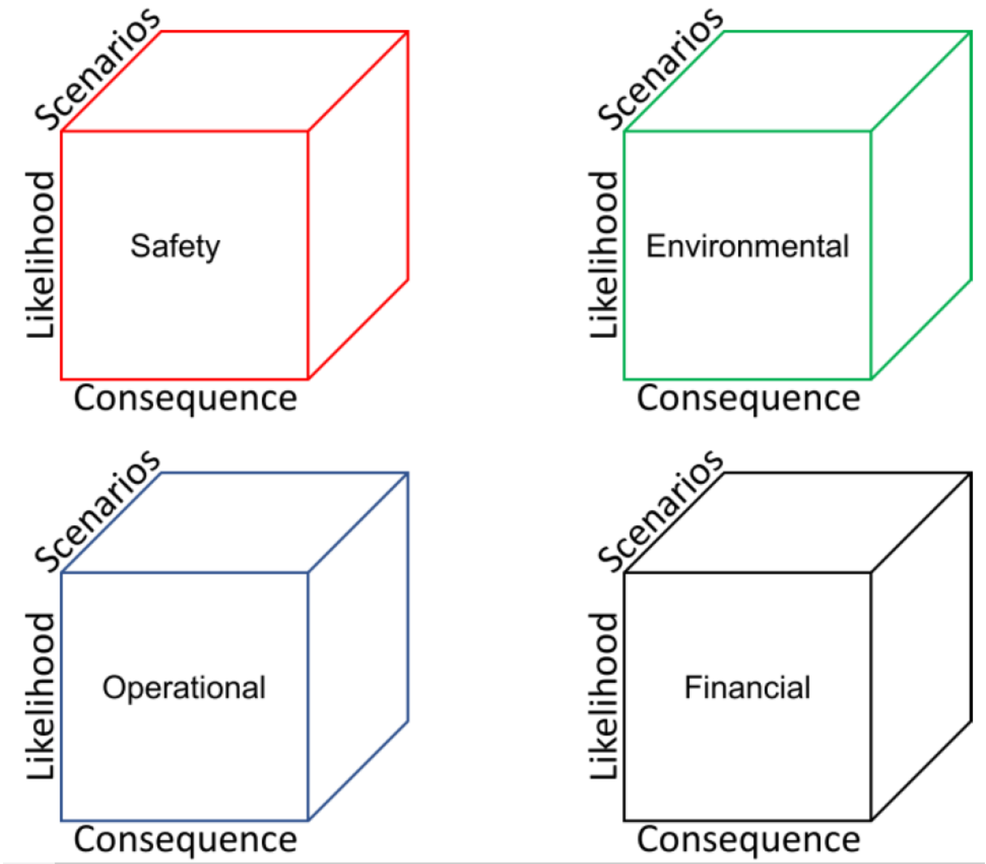

Figure 11: Inherent risk assessment cubes

3.4.6. Decision Logic

As depicted in Figure 12, the AAPM approach proposes an enhanced revision of the classical RCM decision diagram (SAE JA 1012) to help the AAPM team identify the best maintenance type to mitigate each failure mode with an inherent risk higher than the acceptable risk limit.

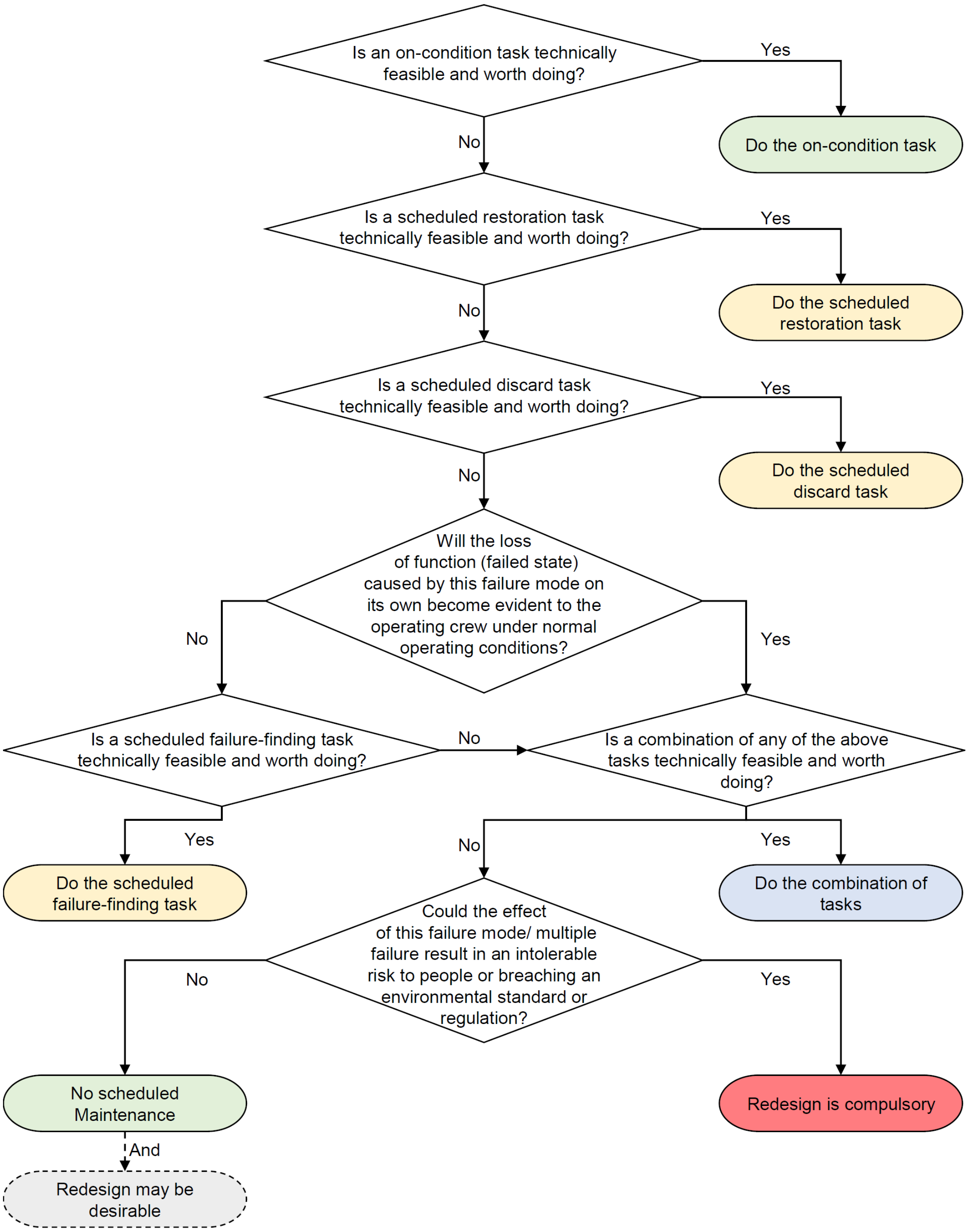

Figure 12: AAPM decision logic

3.4.7. AAPM Action

Based on the recommended maintenance type from the previous step (decision logic), which could be:

- On-condition Action: such as vibration monitoring, oil analysis, etc.
- Scheduled restoration Action: such as overhauls, refurbishment, etc.
- Scheduled discard Action: it means schedule replacement of maintainable items such as bearing replacement.
- Failure finding Action: it is the task performed to address hidden failures. Examples of this task include a start-stop test of standby assets and functional testing of protection devices.
- Redesign Action

The AAPM team discusses every action description, frequency, duration, and resources required. Figure 13 depicts how step 7 in the *"start analysis"* process transfers all AAPM actions to the "*shape packages"* process.

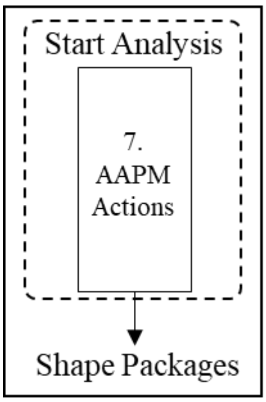

Figure 13: AAPM actions transfer

3.4.8. Residual Risk Assessment

The last step in AAPM is the failure mode residual risk assessment, in which the team reassesses the risk, considering the recommended actions in the previous step. When the AAPM assess the recommended task residual risk, the team considers the action impact on the inherent risk value for every scenario. For an AAPM action to be qualified, it has to reduce the residual risk value below the inherent risk value; otherwise, the action shall be reviewed and validated. Figure 14 shows how the residual risk value influences the *"sharpen more",* which compares it against the stakeholders' risk expectations. Also, it depicts the connection with the *"standardise execution"* process to update the residual risk value in case of reoccurrence of AAPM listed (existing) failure mode.

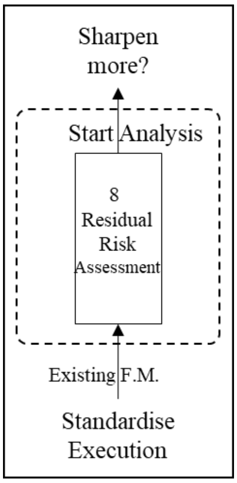

Figure 14: Residual risk updates

3.5. Shape Packages

Several research papers have discussed the prioritisation and selection between different maintenance packages, such as the work done by Tam and Price (2008) to maximise the return on maintenance investment under time and budget constraints (Tam & Price, 2008). The AAPM tries to achieve the same objective differently by using a dedicated maintenance package for each dominant operating context scenario rather than using a single maintenance package.

The *"shape packages"* process is responsible for grouping the received AAPM actions from the *"start analysis"* process into actions' packages where every specified dominant scenario has a dedicated package.

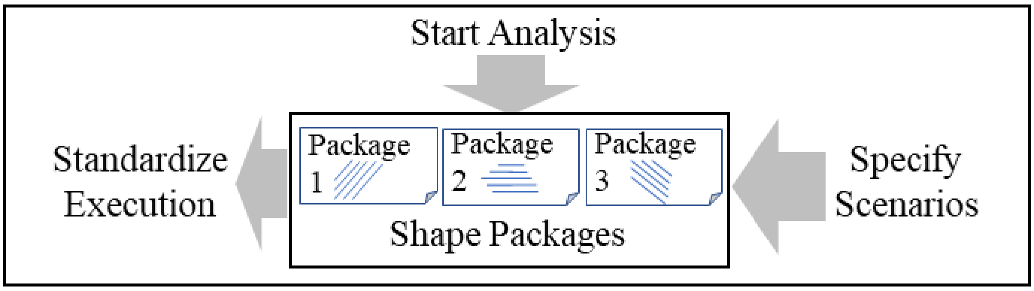

Figure 15: "Shape packages" process

As shown in Figure 15, there are three actions' packages resulting from having three operating context scenarios—however, only one package at a time to be active and executed. The *"shape packages"* process switches from one package to another according to operating context scenarios fluctuations. So it integrates with the *"specify scenarios"* process to link each package with the corresponding scenario trigger to activate the package once the linked scenario occurs. Then, the active package is migrated to the *"standardise execution"* process for implementation according to the operating context scenario in place.

3.5.1. AAPM Actions' Package

The AAPM actions' package consists of three blocks static, dynamic, and resources block.

1) Static Block

This block groups all the AAPM actions created against AAPM static functions which are identical across all packages, as depicted in Figure 16.

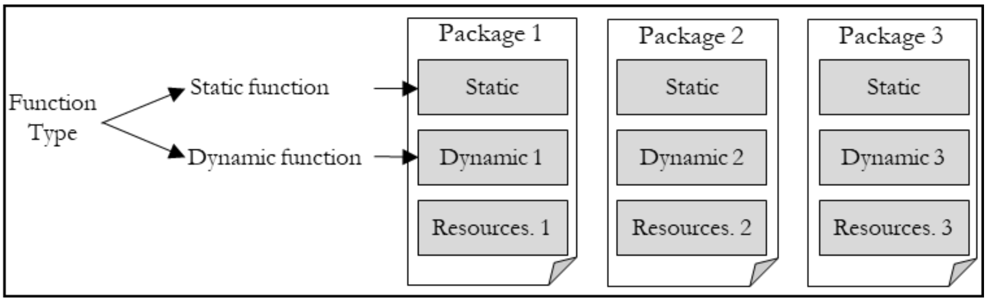

Figure 16: AAPM actions' package structure

2) Dynamic Block

This block groups all actions created against the AAPM dynamic functions. This block is different from one package to another, as the recommended actions are scenario dependent.

3) Resources Block

This block provides all the information needed by the maintenance planner to plan and schedule the AAPM actions' package. This information may include the man-hours, the spares, pre-requisites, and any additional resources.

3.5.2. Activate / Deactivate Package

The *"shape packages"* process assures that only one package is active at a time. It utilises the scenario triggers from the *"specify scenarios"* process to activate a scenario and deactivate another. For instance, in Figure 7, when the market demand changes from high to low level while the cost of energy remains expensive, this should deactivate package (1) and activate package (3). The following table shows how the triggers activate and deactivate the different packages.

Table 4: Operating context scenarios' triggers

Scenario #	Triggers		Actions' Package
	Cost of Energy	Market Demand	
1	Expensive	High	Package 1
2	Cheap	High	Package 2
3	Expensive	Low	Package 3
4	Cheap	Low	Package 4

3.6. Standardise execution

Data quality is a typical implementation challenge, and this happens when the asset owners give a lower priority to failures and maintenance data reporting and focus only on completing the repair activity to return the asset to service and restart the production quickly. Therefore, the AAPM framework proposes the *"standardise execution"* process to overcome this challenge. It integrates the AAPM database and the CMMS database to capture new failure modes or update the residual risk of existing failure modes. Thus, the proper implementation of this process assures the continuous improvement of CMMS data quality.

As depicted in Figure 17, the *"standardise execution"* manages the execution of AAPM actions'; it also sends the preventive work history data to the "sharpen more" process that compares actual cost figures against stakeholders' expectations. Besides, it sends the corrective work history data to the *"supervise results"* process to calculate and trend the corrective work performance indicators.

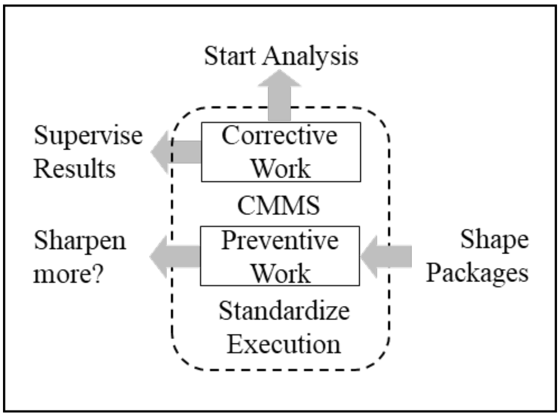

Figure 17: "Standardise execution" process

3.6.1. Corrective Work

It is the repair carried out after the asset failure to restore the asset into a state in which it can perform a required function. The corrective work data management plays a significant role in keeping the AAPM framework evergreen, so whenever a new failure mode shows up, its data (observation, maintainable item, damage, and cause) is used to create a new failure mode record in the AAPM database. While for the listed failure modes in the AAPM database, the reoccurrence of any of them impacts the probability level in the residual risk assessment step and might result in a need to modify the assigned mitigation action. The corrective work has two main classes immediate and deferred work (BSI.13306, 2017, p. 38).

1) Immediate Corrective Work

The immediate corrective work is the work that is carried out immediately after the asset failure detection to avoid unacceptable consequences.

2) Deferred Corrective Work

The deferred corrective work is the corrective work that is not immediately carried out after detecting asset failure, but it is delayed according to given rules in place.

3.6.2. Preventive Work

Preventive work is carried out to assess and mitigate degradation and reduce the probability of failure of an asset; this work has two main classes, pre-determined and condition-based maintenance (BSI.13306, 2017, p. 35).

1) Pre-determined Maintenance

It is the preventive work carried out in accordance with established intervals of time or number of units of use but without previous condition investigation

2) Condition Based Maintenance

It is the type of preventive work that includes assessing physical conditions, analysis and the possible ensuing maintenance actions. This work may be by operator observation, inspection, testing, condition monitoring of system parameters, etc., conducted according to a schedule, on request or continuous.

3.6.3. Switching Between Actions' Packages

The AAPM framework implements the actions' packages as part of the preventive work, which considers the implementation of one active package at a time. When changing between packages, the schedule of the static block actions remains the same, while the schedule of the dynamic block actions may need a review if the activated package includes actions that exist in the deactivated package.

For instance, assume the deactivated package has action x with a frequency of (1) year while the activated package has the same action x but with a frequency of (6) months. In this case, the transition between the packages schedules the next execution date of action x after (6) months of the last execution during the deactivated package.

3.7. Supervise Results

The absence of program auditing besides the use of misleading KPI's are potential contributing factors in the failure of any asset performance improvement initiative. Having a well-structured auditing procedure is crucial as the failure in maintaining a consistent quality assurance process that reviews and approve the optimisation task may result in a long list of outstanding recommendations and stakeholder's frustration. Also, some organisations apply KPI's that focus on quantity rather than quality, so they measure the productivity in terms of the number of assets analysed or the number of failure modes identified; this usually results in a poor-quality deliverable and almost zero return.

The proposed *"supervise results"* process tries to resolve these two issues as it monitors the effectiveness of AAPM actions through the evaluation and prediction of RAM and cost. The process helps avoid the potential failure of the AAPM program due to poor performance tracking as it evaluates the effect of AAPM actions' packages on the system/asset reliability. Besides, it utilises the corrective work history data received from the *"standardise execution"* process to assess and predict work cost and frequency. As depicted in Figure 18, the outcomes of this process help in deciding whether a better solution is needed or not through the *"sharpen more"* process.

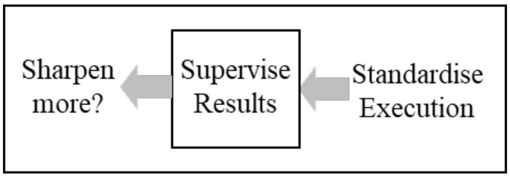

Figure 18: "Supervise results" process

To assess and predict the changes in the corrective work cost and frequency, AAPM uses the reliability growth analysis. Also, this tool enables AAPM to identify opportunities for improvement, which a typical application of reliability growth as highlighted in several papers. For instance, Shamayleh, Awad and Abdulla (2019) had suggested a method that depends on the reliability growth analysis for opportunity identification in their approach of medical equipment maintenance task selection (Shamayleh, et al., 2019, p. 311)

3.7.1. Corrective Work Cost Assessment

In this illustrative example (Figure *19*), the vertical axis represents the cumulative cost of the corrective work, while the horizontal axis indicates the cumulative operating time, and each dot on the plotting area represent a corrective work event (failure). For instance, the second failure occurred at 90 accumulative hours, while the fourth failure happened at 500 accumulative hours. The blue line is the best-fit line to the failure data points, and it is divided into two segments at the point of commencing the execution of AAPM actions' packages. The segments demonstrate the performance before and after the AAPM actions' packages execution, where the less line slop (beta value), the better the performance is.

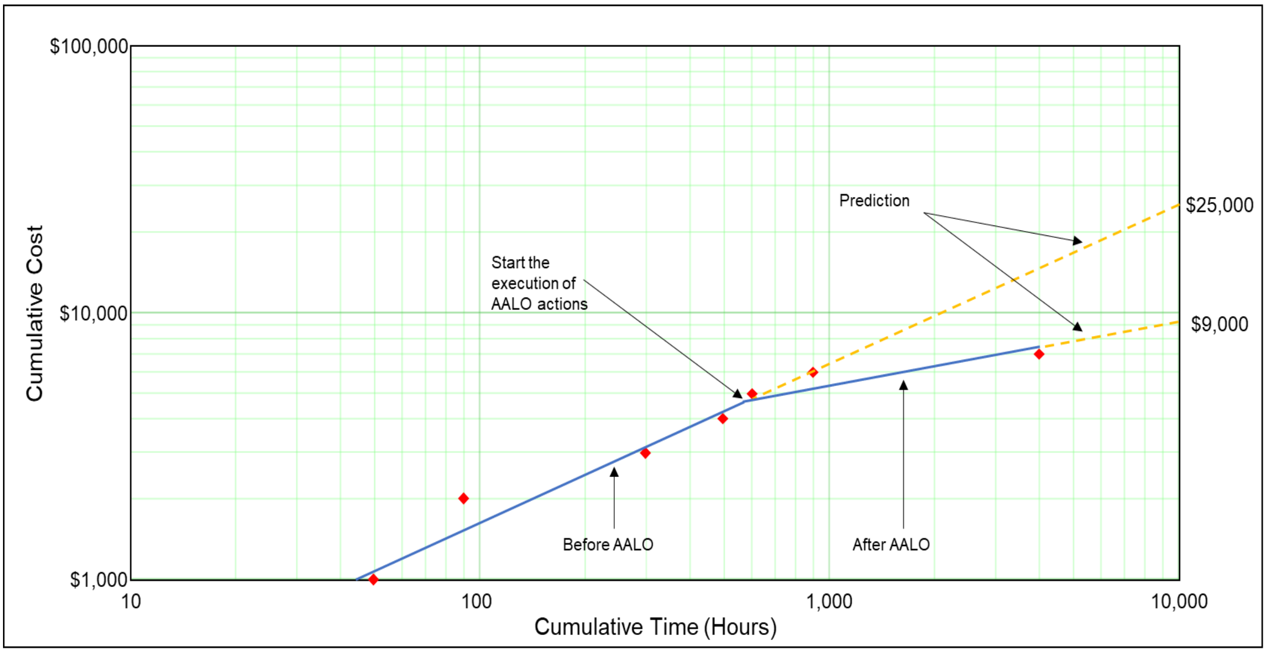

Figure 19: Illustrative graph of corrective work cost assessment

As depicted in this illustrative example, The AAPM actions' packages executions are expected to result in a total cost of $9,000 at 10,000 Hrs, which is less than the expected result if AAPM action not executed ($25,000). This corrective work cost here includes repair cost, production loss cost, any additional financial losses as a direct result of this event.

3.7.2. Corrective Work Frequency Assessment

Figure 20 shows an illustrative graph where the vertical axis represents the cumulative failures (the number of failures) and the horizontal axis indicates the cumulative operating time. Also, each dot on the plotting area indicates a failure; for instance, failure 1 occurred after 50 hours of operation, while failure 2 happened after 40 hours from failure 1.

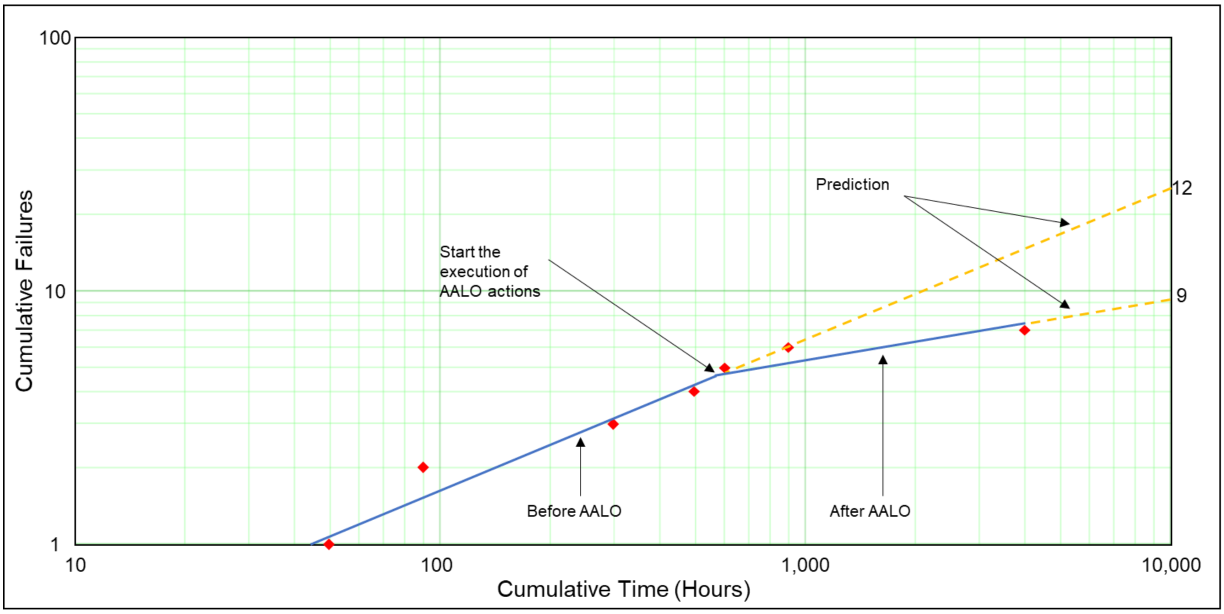

Figure 20: Illustrative graph of corrective work frequency assessment

In this illustrative example, the blue line is the best-fit line to the failure data points, and this line has been divided into two segments. The first segment is trending the performance before AAPM actions' packages, and it shows a significant increase in the rate of failures that could lead to more than 11 failures by 10,000 operating hours. The second segment shows the performance after commencing the execution of AAPM actions' packages, and it is showing an enhancement that will lead to almost nine failures by 10,000 operating hours.

3.8. Sharpen more

The *"sharpen more"* process is the AAPM checkpoint that justifies if a better solution is needed or not; through the constant comparison of AAPM results against the asset/system stakeholders' expectations received from the *"set expectations"* process. As depicted in Figure 22, the *"sharpen more"* process receives the corrective work cost and frequency figures from the *"supervise results"* process. Also, it gets the preventive work cost numbers from the *"standardise execution"* process. Besides, it receives the residual risk profile from the *"start analysis"* process to compare against the acceptable risk thresholds. Then the process may trigger an analysis review and update request to the *"start analysis"* process if the outcome of the decision is "yes". On the other side, if the decision is "no", it will keep monitoring the stakeholders' expectations to trigger the AAPM process if the expectations change.

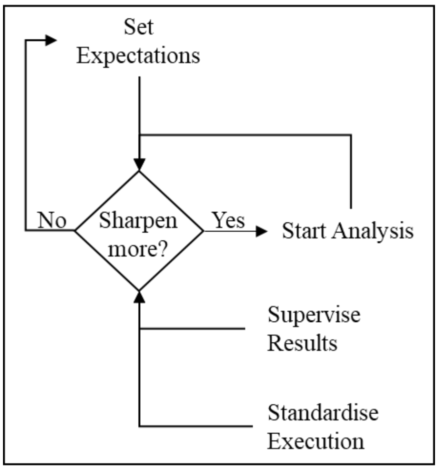

Figure 21: "Sharpen more" process

This process uses stakeholders' agreement of expectations template as explained in Table 1 to monitor the progress in meeting the predefined expectations within the three main expectations pillars.

3.8.1. RAM

The *"sharpen more"* process calculates periodically the actual values of RAM indicators based on the received corrective and preventive work data.

3.8.2. Cost

The *"sharpen more"* process compares the preventive work cost received from the *"standardise execution"* process and the corrective work cost received from the *"supervise results"* process against the stakeholders' agreement of expectations in Table 1.

3.8.3. Residual Risk Profile

As discussed earlier, the *"standardise execution"* process updates the "residual risk assessment" step in the *"start analysis"* process according to the reoccurrence of AAPM listed failure modes. This update in the probability scale changes the residual risk value, which needs to be within the acceptable risk thresholds as defined in the *"set expectations"* process.

As depicted in Figure 22, AAPM employees the heat map to monitor the changes in the residual risk for every AAPM listed failure mode; it also tracks the impact of each AAPM actions' package on the residual risk profile.

However, the heat map has been used in several applications, such as the measure of cybersecurity risk awareness of various roles within organisations (Kour & Karim, 2020); the AAPM framework innovatively introduces this tool to monitor the correlation between maintenance packages, failure modes, and residual risk.

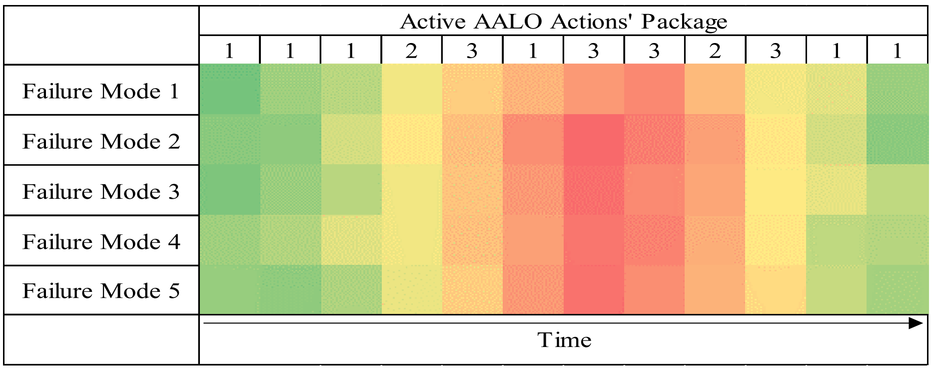

Figure 22: Residual risk heat map

Hence, the *"sharpen more"* process continuously monitors the risk profile to spot any failure mode with a residual risk value out of the acceptable risk thresholds for AAPM detailed review through the *"start analysis"* process.

4. Agile Asset Performance Management Conceptual Framework

Considering the eight processes discussed in the previous section, Figure 23 depicts the comprehensive framework of AAPM, which shows the interrelationships between these processes. As described in Figure 23, the framework starts with the *"select asset"* process, which selects and prioritises assets for AAPM implementation based on asset's performance, criticality, and readiness for implementation. Then, it feeds a list of qualified assets with its priorities to the second process.

The *"set expectations"* process identifies the current performance and stakeholders expectations of AAPM implementation on the qualified assets in terms of RAM, cost, and risk. Then, process eight uses the identified expectations as a reference point to evaluate the implementation. Also, the identified expectations influence and reshape the operating context parameters in the third process.

The *"specify scenario"* process feeds the fourth process with the probable scenarios to be considered during the analysis. Also, it triggers the fifth process to activate and deactivate the relevant actions' package according to the changes in operating scenarios.

The *"start analysis"* process identifies and delivers the mitigating actions to the fifth process, which creates the different actions' packages. Besides, it feeds back the residual risks to the last process to decide if a better solution is needed.

The *"shape packages"* process categorises the received actions from the fourth process into different packages where each package addresses a specific operating scenario. It also orchestrating the activation of actions' packages according to the received triggers from the third process;

The *"standardise execution"* process integrates with the fourth process to keep its database of failure modes updated with any new failure mode information. Also, it updates the "residual risk" step in case of the reoccurrence of a listed (existing) failure mode.

The *"supervise results"* process evaluates and predicts the cost and frequency of corrective work based on the data received from the sixth process, and then it feeds the results to the last process.

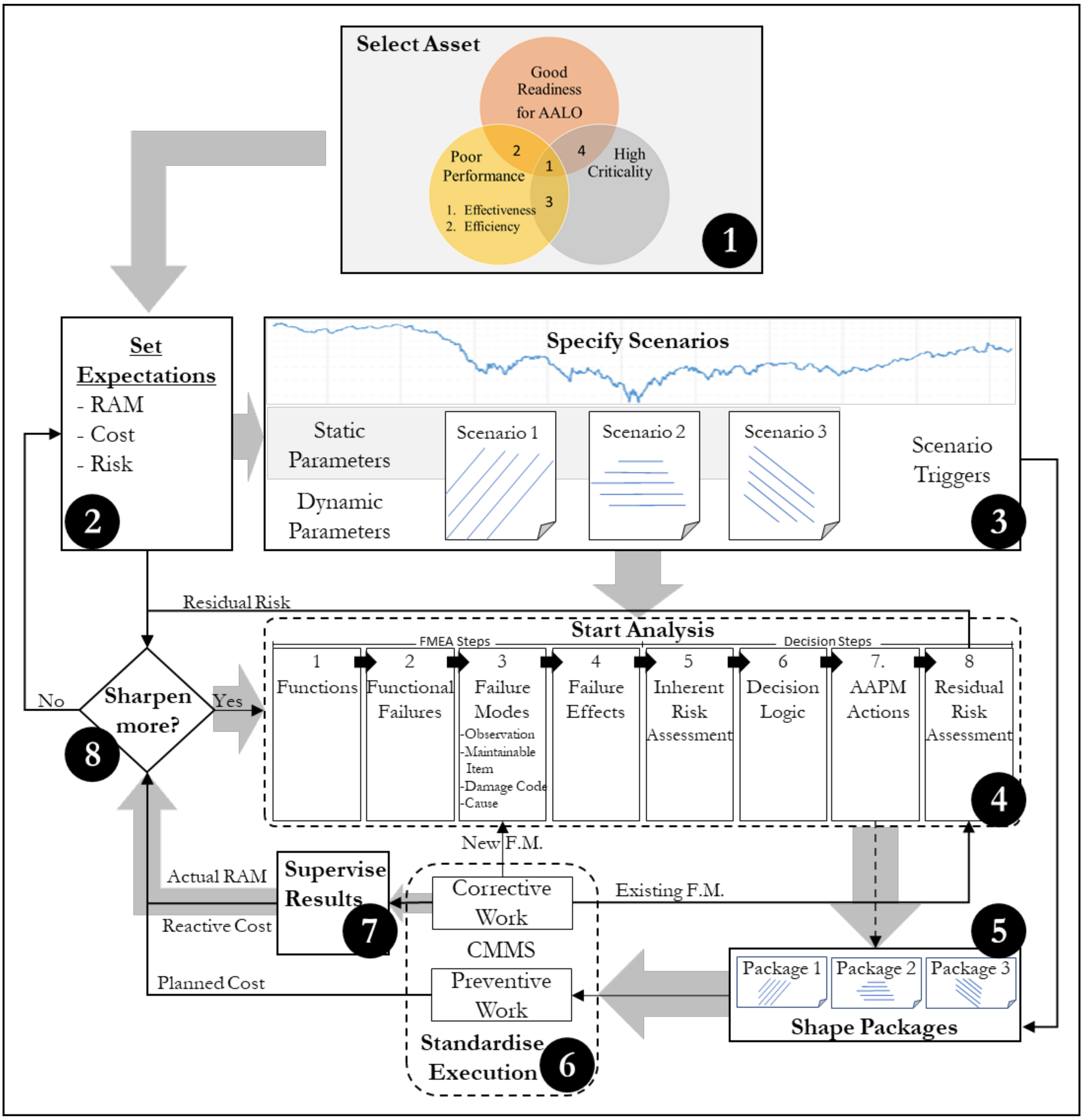

Figure 23: AAPM Framework

4.1. Learning from success and failures

The AAPM framework learns from success and failures at both the asset level and the failure mode level. At the asset level, the *"sharpen more"* process utilises the cost figures received from the sixth and seventh processes besides the residual risk profile received from the fourth process to evaluate the overall performance against the stakeholders' expectations from the second process. Then, it triggers the review of the analysis in process four if the results are not meeting the expectations; otherwise, it keeps monitoring the changes in stakeholders' expectations to trigger the third process accordingly.

At the failure mode level, once a listed (existing) failure mode reoccur again, the "corrective work" step feedbacks to the "residual risk assessment" step to increase the residual risk probability, as the failure mode's residual risk probability increases as the residual risk value increase. If the residual risk value exceeds the inherent risk value then, a task review process will be triggered to review and amend the mitigating action, as depicted in Figure 24. In order to maintain the residual risk value less than the inherent risk, additional mitigating actions could be added or increasing the frequency of the existing action.

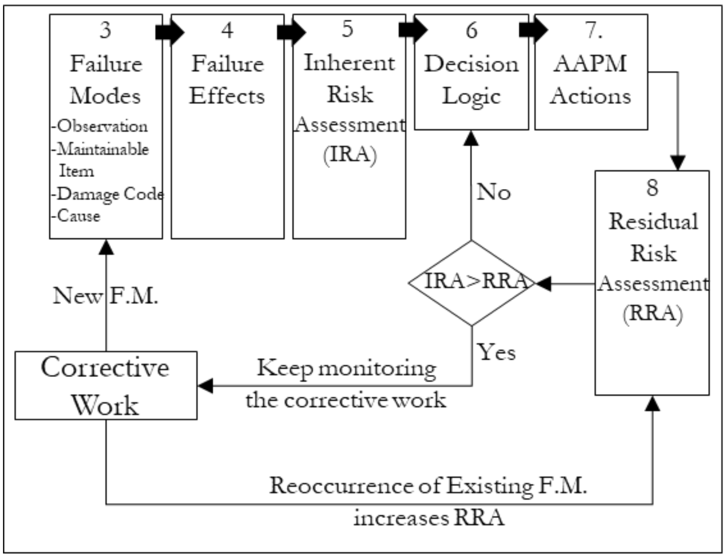

Figure 24: Reoccurrence of existing failure mode

4.2. AAPM as an integrated asset management system

However, the framework utilises a few well-known tools, the real contribution of this framework lies in the strong integration it provides between the different tools to form an integrated system that enables organisations to consolidate the different working silos under one umbrella. The approach promotes a more streamlined communication between the maintenance planners, reliability engineers, risk specialist and other stakeholders centralised around the asset health, which enables a systematise and operationalise decision-making process

The proposed AAPM helps asset owners move away from using several point solutions that manage isolated processes toward the integrated enterprise asset management systems that consolidate the different work processes and break the silo working, increasing efficiency and maximising return. This move requires more attention from the research community to increase the reliability and asset management tools' efficiency through innovative integration.

5. Discussion

The integration between the eight "S" processes proposed in this paper has resulted in a comprehensive, unified framework. As shown in Figure 23, the eight processes are interconnected so that any change in the stakeholders' expectations, operating context, or asset reliability triggers the framework to find a better solution (maintenance package) accordingly.

While designing the inherent and residual risk assessment steps within the *"start analysis"* process, the need for a unique risk assessment tool has been revealed. This has resulted in developing the risk assessment cube as a three-dimensional risk assessment tool that considers the changes in the operating context scenario beside the consequences and likelihood dimensions.

Developing the *"supervise results"* process has led to the adoption of the reliability growth analysis as a performance monitoring, trending, and prediction tool for corrective work cost and frequency, this early prediction of corrective work cost and frequency enables the framework to respond proactively and triggers the *“start analysis”* process to adjust the preventive work accordingly.

Furthermore, the integration between the *“sharpen more”* process and the “residual risk assessment” step within the *“start analysis”* process has guided the authors to select the heat map as a risk monitoring and communication tool. The residual risk heat map application as part of the AAPM framework enables further analysis to determine the correlations between AAPM actions' package effectiveness, residual risk profile, and time.

In summary, the development of the proposed comprehensive framework has led to the identification and employment of several tools in such an innovative integrated way that expected to enable and streamline the asset performance management process.

6. Conclusion

This paper proposes an agile asset performance management framework using the 8S approach; it explains the suggested 8S processes in detail, focusing on the interrelationship and connections between steps to demonstrate the framework's integrity.

The research responds to the asset management community's need for a detailed guide that gears different reliability tools to overcome silo working challenge and connect all asset stakeholders on the same platform. Also, The research highlights the value of CMMS data and the importance of linking it to a dynamic failure mode database to update the failure mode criticality timely and validate the cost of mitigating maintenance actions. Therefore, the implementation of AAPM is expected to promote the practical use of reliability tools such as growth analysis, enhance CMMS data quality, improve asset stakeholders communications, minimise the risk and optimise the cost.

However, the "select asset" process identifies three fundamental components of the selection criteria (readiness, performance, and criticality), the relative weights have not been addressed, which represents an interesting point for further work to complement this process. Also, managing stakeholders' competing expectations, such as risk reduction and cost-cutting in the *"set expectations"* process, needs more exploration. Besides, the calculations of return on investment (ROI) from each actions package or even from each action is a must to secure the framework's successful practical implementation. Thus, creating a methodology for the ROI calculations and each action or package's relative importance is an exciting area for future research.

References

1) Adams, J., Srinivasan, R., A. K. P. & González-Prida, V., 2016. *Towards Dynamic Criticality-Based Maintenance Strategy for Industrial Assets.* s.l., International Federation of Automatic Control, pp. 103-107.
2) Ahmed, M. N., 2020. The use of performance-based contracting in managing the outsourcing of a reliability-centered maintenance program - A case study. *Journal of Quality in Maintenance Engineering,* 26(4), pp. 526-554.
3) Aven, T. & Zio, E., 2021. Globalization and global risk: How risk analysis needs to be enhanced to be effective in confronting current threats. *Reliability Engineering and System Safety,* Volume 205.
4) Braaksma, A., Klingenberg, W. & Veldman, J., 2013. Failure mode and effect analysis in asset maintenance: a multiple case study in the process industry. *International Journal of Production Research,* 51(4), pp. 1055-1071.
5) BSI.13306, 2017. *BS En 13306:2017 Maintenance — Maintenance terminology,* s.l.: British Standard.
6) Carnero, M. C. & Novés, J. L., 2006. Production Planning and Control. *Selection of computerised maintenance management system by means of multicriteria methods,* 17(4), pp. 335-354.
7) Dui, H., Si, S., Wu, S. & Yam, R. C., 2017. An importance measure for multistate systems with external factors. *Reliability Engineering and System Safety,* Volume 167, pp. 49-57.
8) Eti , M., Ogaji, S. & Probert, S., 2006. Reducing the cost of preventive maintenance (PM) through adopting a proactive reliability-focused culture. *Applied Energy,* 83(11), pp. 1235-1248.
9) Gupta, G. & Mishra, R. P., 2016. A SWOT analysis of reliability centered maintenance framework. *Journal of Quality in Maintenance Engineering,* 22(2), pp. 130-145.

10) Hajej, Z. & Rezg, N., 2020. An optimal integrated lot sizing and maintenance strategy for multi-machines system with energy consumption. *International Journal of Production Research,* 58(14), pp. 4450-4470.

11) Holgado, M., Macchi, M. & Evans, S., 2020. Exploring the impacts and contributions of maintenance function for sustainable manufacturing. *International Journal of Production Research,* 58(23), p. 7292–7310.

12) ISO.14224, 2016. *Petroleum, petrochemical and natural gas industries Collection and exchange of reliability and maintenance data for equipment,* s.l.: ISO.

13) Karar, A. N. & Labib, A., 2020. Agile asset criticality assessment approach using decision-making grid. *Journal of Quality in Maintenance Engineering.*

14) Kour, R. & Karim, R., 2020. Cybersecurity workforce in railway: its maturity and awareness. *Journal of Quality in Maintenance Engineering.*

15) Labib, A., 2003. Computerised Maintenance Management Systems: A Black Hole or a Black Box?. *Maintenance and Asset Management,* 18(3), pp. 16-20.

16) Labib, A., 2004. A decision analysis model for maintenance policy selection using a CMMS. *Journal of Quality in Maintenance Engineering.*

17) Labib, A. W., 1998. World-class maintenance using a computerised maintenance management system. *Journal of Quality in Maintenance Engineering*, pp. 66-75.

18) Labib, A. W., Williams, G. B. & O'Connor, R. F., 1997. Deriving a maintenance strategy through the application of a multiple criteria decision making methodology. *Springer, Berlin, Heidelberg.,* pp. 481-490.

19) Lanzrath, M., Suhrke, M. & Hirsch, H., 2020. HPEM-Based Risk Assessment of Substations Enabled for the Smart Grid. *IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY,* 62(1).

20) Lee, J. et al., 2013. Development of Computerized Facility Maintenance Management System Based on Reliability Centered Maintenance and Automated Data Gathering. *International Journal of Control and Automation,* 6(1).

21) macrotrends, 2020. *macrotrends.* [Online] Available at: https://www.macrotrends.net/futures/crude-oil [Accessed 23 05 2020].

22) Martinetti, A., Schakel, E. J. & Dongen, . L. A. v., 2018. Flying asset - Framework for developing scalable maintenance program for unmanned aircraft systems (UAS). *Journal of Quality in Maintenance Engineering,* 24(2), pp. 152-169.

23) Piechnicki, F., Dos Santos, C. F., Loures, E. D. F. R. & Dos Santos, E. A. P., 2020. Data fusion framework for decision-making support in reliability-centered maintenance. *Journal of Industrial and Production Engineering.*

24) SAE.JA.1012, 2002. A Guide to the Reliability-Centered Maintenance (RCM) Standard.

25) Sahnoun, M. et al., 2015. Modelling and simulation of operation and maintenance strategy for offshore wind farms based on multi-agent system. *Journal of Intelligent Manufacturing,* Volume 30, p. 2981–2997.

26) Selvik, J. & Aven, T., 2011. A framework for reliability and risk centered maintenance. *Reliability Engineering and System Safety,* Volume 96, pp. 324-331.

27) Shamayleh, A., Awad, M. & Abdulla, A. O., 2019. Criticality-based reliability-centered maintenance for healthcare. *Journal of Quality in Maintenance Engineering,* 26(2), pp. 311-334.

28) Statista, 2020. *Statista.* [Online] Available at: https://www.statista.com/statistics/322996/monthly-electricity-consumption-from-all-electricity-suppliers-in-the-united-kingdom-uk/ [Accessed 25 05 2020].

29) Stenström, C., Norrbin, P., Parida, A. & Kumar, U., 2016. Preventive and corrective maintenance – cost comparison and cost–benefit analysis. *Structure and Infrastructure Engineering,* 12(5).

30) Stuchlý, V., Poprocký, R. & Kaczmarek, M., 2016. RELIABILITY EVALUATION AS A MEANS OF INCREASING THE EFFICIENCY OF EQUIPMENT MAINTENANCE. *Advances in Science and Technology,* 10(32), pp. 40-46.

31) Tam, A. S. & Price, J. W., 2008. METHODOLOGY AND THEORY A maintenance prioritisation approach to maximise return on investment subject to time and budget constraints. *Journal of Quality in Maintenance Engineering,* 14(3), pp. 272-289.

32) TOMLIN, B. & WANG, Y., 2011. Operational Strategies for Managing Supply Chain Disruption Risk. In: *Handbook of Integrated Risk Management in Global Supply Chains.* s.l.:s.n., pp. 79-101.

33) Wang, Y., Yam, R. C., Zuo, M. J. & Tse, P., 2001. A comprehensive reliability allocation method for design of CNC lathes. *Reliability Engineering and System Safety,* 72(3), pp. 247-252.

34) Wu, K., Liu, T., Yu, Z. & Chen, L., 2017. Signal conditioning units for vibration measurement in HUMS.

35) Wu, S., Chen, Y., Wu, Q. & Wang, Z., 2016. Linking component importance to optimisation of preventive maintenance policy. *Reliability Engineering and System Safety,* Volume 146, pp. 26-32.

36) Yang, L., Zhao, Y., Peng, R. & Ma, X., 2018. Hybrid preventive maintenance of competing failures under random environment. *Reliability Engineering and System Safety,* Volume 174, pp. 130-140.

37) Zhou, D., Zhang, H., Li, Y.-G. & Weng, S., 2015. A Dynamic Reliability-Centered Maintenance Analysis Method for Natural Gas Compressor Station Based on Diagnostic and

Prognostic Technology. *Journal of Engineering for Gas Turbines and Power,* 138(6), pp. 061601-1:9.